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Recent Progress at the Keck Interferometer

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ABSTRACT

In this paper we report on progress at the Keck Interferometer since the 2004 SPIE meeting[1] with an emphasis on the operations improvements for visibility science.

Keywords: Interferometer, operations, visibility, Keck

1. INTRODUCTION

The Keck Interferometer (KI) is a NASA-funded project to combine the two 10-m Keck telescopes for high sensitivity near-infrared fringe visibility measurements and mid-infrared nulling measurements. The KI has been jointly developed by the Jet Propulsion Laboratory, the Michelson Science Center and the W. M. Keck Observatory.

The primary emphasis over the past two years has been on the integration of the nuller system at the Observatory and on developing the nuller performance and science capability through on- and off-sky testing. The nuller development and early science results are discussed elsewhere in this conference.[2,3]

The KI has been performing visibility (V^2) observations since 2001. Science operations began officially with a V^2 operational readiness review in April, 2004.[4] Eight V^2 refereed science papers have been published to date (and one 10 μm V^2 result using the nuller). The V^2 science results are discussed elsewhere in this conference.[5]

This paper focuses on other aspects of progress with the KI beginning with an overview of operations and followed by discussions of the performance improvements, new capabilities, operations improvements, system characterization and science support. We close with our plans for the next couple of years.

2. OPERATIONS OVERVIEW

The KI is currently operated on the sky for a total of ~ 30 nights per year. The majority of these nights (19 nights in 2006) are being used to support nuller on-sky engineering and initial science in support of this engineering. These nights are typically divided into bi-monthly 3 night runs per year. About two nights a year are used for other engineering purposes, primarily V^2 but also some nights have been used in support of the 'OHANA[6] project. The remaining ~10 nights per year are allocated by the NASA, Caltech and University of California time allocation committees (TACs) for V^2 science. There are typically four V^2 runs per year.

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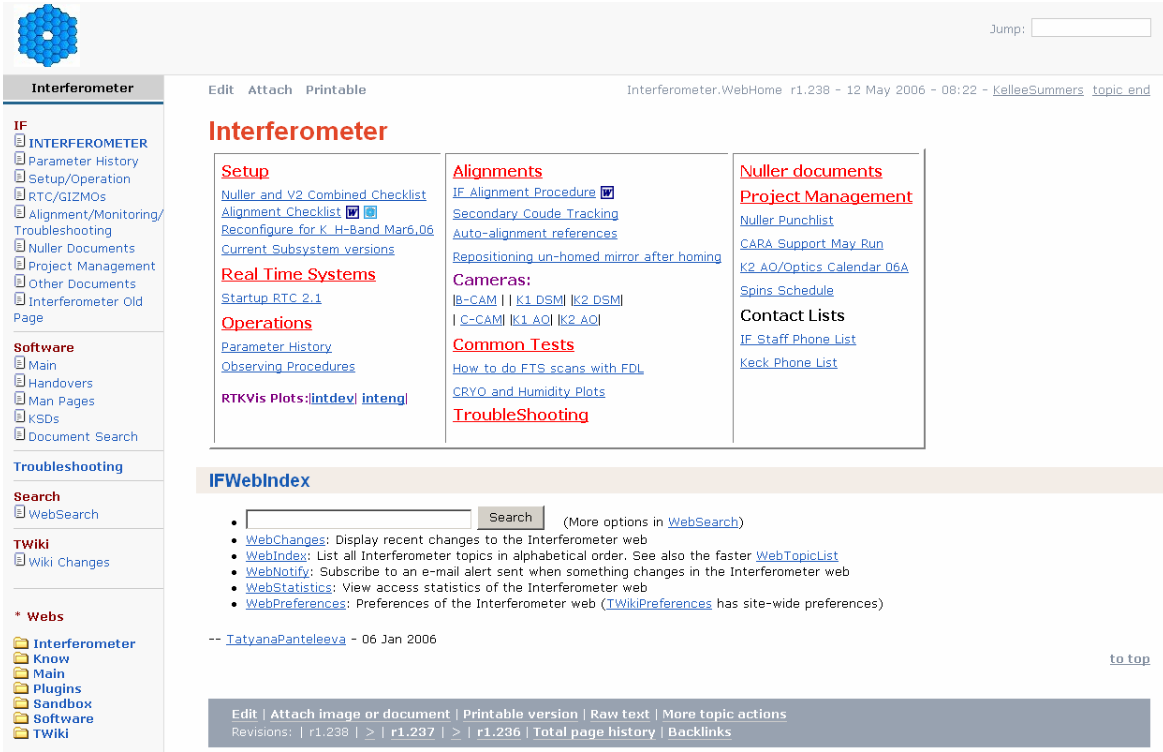

Figure 1 Web interface to operations documentation.

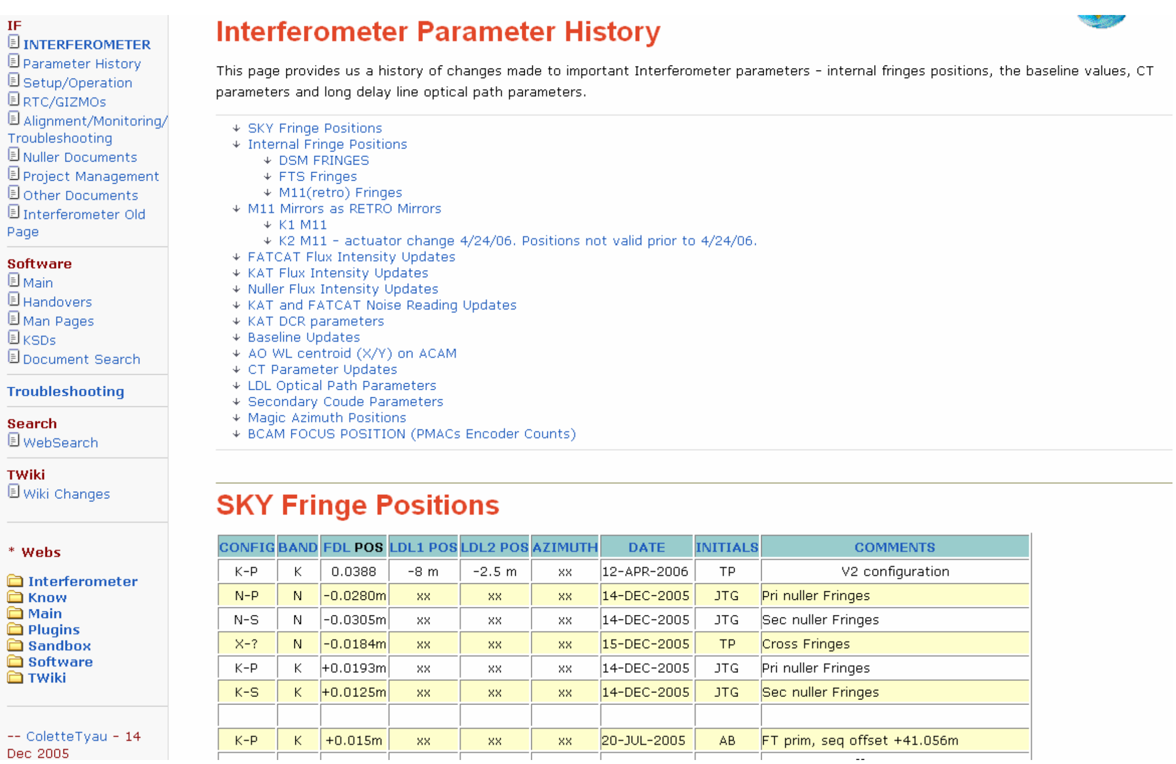

Figure 2 Parameter history maintained by the Twiki tool.

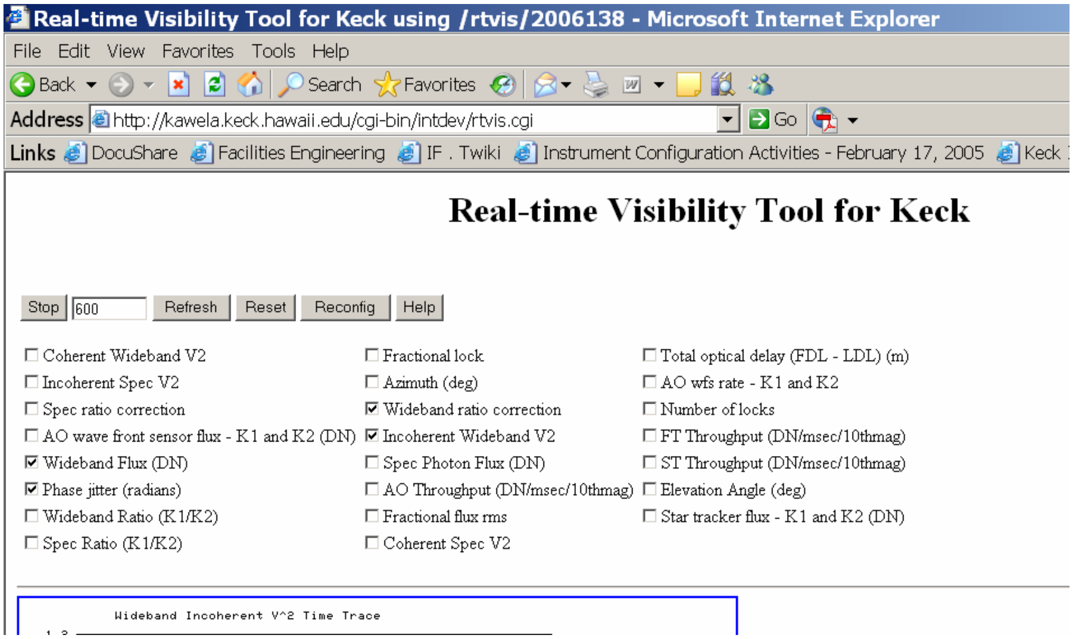

Figure 3 Real-time Visibility tool.

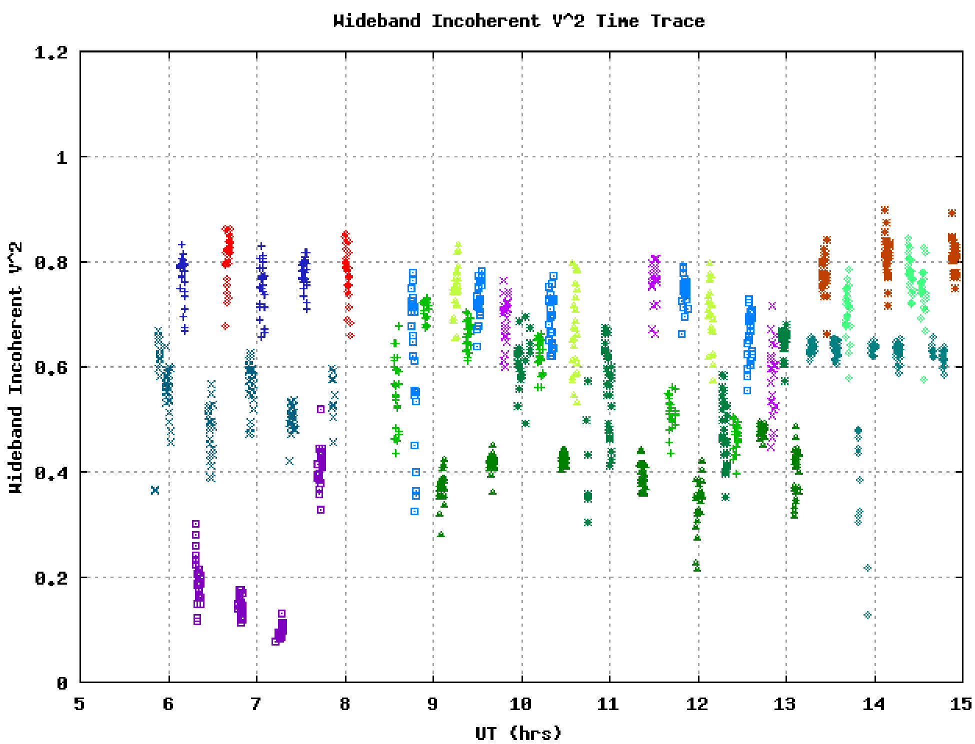

Figure 4 Real-time visibility plot for a night during the May, 2006 V^2 run. Each symbol represents a different science target or calibrator star and each data point corresponds to 5 sec of data or 125 sec per scan. An average of 6.3 scans per hour was achieved over the night. The 25 and 15 min gaps in the data starting at 8:26 and 11:05, respectively, are due to repositioning of the long delay lines.

All documentation in support of operations is available through the web (Twiki) interface shown in Figure 1. Living documents (documentation that requires frequent updating such as the parameter history shown in Figure 2) are maintained directly through the Twiki web interface, while all other documentation is maintained on the Keck docushare site with operational access provided through the Twiki. Both tools offer standard document control tools such as configuration management and search capabilities.

Daytime and pre-observing checklists are used to ensure that the KI and the Observatory environment are properly setup for nighttime operations. This is especially important since the KI nuller mode is still under development and there are large gaps between V^2 observing runs.

The KI archiver records the parameter history of most of the real-time hardware subsystem. During an average V^2 science night 20 Gigabytes of data are archived. The MSC has developed a set of tools to produce quick-look science products from this archive. The MSC real-time visibility tool shown in Figure 3 is routinely used at night for understanding the quality of the science data and for quickly checking for problems. Figure 4 shows one of these quick-look plots.

A configuration control board (CCB) manages changes to the KI instrument in order to protect operational capabilities while facilitating the development of new functionality. All changes to subsystems under configuration control require an engineering change request to be reviewed and accepted. Field changes are allowed with proper documentation.

Routine preventative maintenance (PM) tasks are entered in the Observatory's PM system which releases pre-defined tasks based on the requested schedule. Spares are inventoried in the Observatory's spares tracking system.

3. PERFORMANCE IMPROVEMENTS

The KI K-band sensitivity has been improved from K=9 to K~10 by a combination of software and hardware, plus procedural, changes. These changes were primarily performed in support of nuller development but have also been released for V^2 operations.

For the fringe tracker, phasor coadding was implemented to combine the summed spectrometer channel signal with the white light signal to provide increased flux for tracking. In addition, the algorithm for estimating SNR (which is used for transitioning among search, semi-lock and lock states) was replaced with a lower noise version that still retains the scintillation invariance of the original estimator.

With respect to hardware, a new stimulis was installed which provides a more accurate pupil representation of the incoming starlight; this is now used to optimize alignment and focus onto the single-mode fiber that feeds the fringe tracker camera. The final AO system image sharpening is now also done using raster scans on the fiber (instead of angle tracker images).

Several improvements have been made to angle tracking. An internal dewar realignment moved the optical axis closer to the readout corner of the array, thereby reducing the overhead associated with slews across the array. The angle tracker camera clock generation program was subsequently rewritten to allow faster clocks with more sub-reads. The increased read rate, from 50 to 80 Hz, has improved the tip/tilt sampling, while more sub-reads has decreased the read noise. Grounding improvements have also contributed to reduced noise on the angle tracker.

In an attempt to minimize turbulence along the coude path, pipes have recently been installed to enclose the beams on one of the telescopes. The data is being evaluated to determine the performance impact of this change.

4. NEW CAPABILITIES

The nuller will be available for TAC-allocated shared-risk science in the second half of 2006 and for routine science subsequent to the nuller operational readiness review (scheduled for May, 2007).

The nuller can also be used for V^2 measurements since the null leakage is (1- V^2)/4. While the nulling mode has a lower SNR for V^2 measurements than a dedicated V^2 combiner, it has the significant advantage of providing a quasi-simultaneous peak and null measurement which avoids the need for accurate photometric calibrations (which are difficult without a chopping secondary mirror). Note that V^2 measurements at K-band are simultaneously obtained during nulling.

A grism has recently been implemented in the fringe tracker camera, enabling fringes to be dispersed across 42 channels spanning the K-band (R ~ 230). This has required changes to the way in which the fringe tracker camera is read out and the development of a grism version of the MSC V^2 data reduction pipeline. On May 15 and 16, 2006, the first engineering and science data were acquired with the grism. Preliminary analysis indicates that the spectrally dispersed data can be calibrated reliably to a limiting magnitude of K=6.5. The goal of the first science observations was to investigate the spatial distribution of gaseous emission in protoplanetary disks and evolved stellar atmospheres. Preliminary analysis suggests that the data are suitable for this purpose.

The KI has been used to successfully demonstrate the use of optical fibers for interferometric beam transport as part of the ‘OHANA project.[6] Fiber injection modules were placed on the AO benches and fibers were run from the AO benches to the interferometer basement (bypassing the dual star module, coude optics and some of the beam transport optics). The fiber output was collimated and inserted into the remainder of the KI starting with the long delay lines. Interference fringes were successfully obtained on a star using a pair of 300 m long fibers.

5. OPERATIONS IMPROVEMENTS

A single real-time control software baseline is currently used for both nuller and V^2 operations. The release of this version of the software, developed for the nuller, has resulted in operational improvements (in addition to the V^2 performance improvements discussed above). A common baseline eliminates the need to swap between versions (and hence switching time and the associated risks) and allows for improved operator familiarity.

A number of tools have been developed to better transition the Interferometer from a development phase to an operations phase. These tools allow for a more efficient operator interface, more automation and improved operations reliability.

The Interferometer operator motion control GUI shown in Figure 5 provides users with a visual status of the numerous devices and mirrors which comprise the KI. This has proved valuable for both daytime setup and nighttime operations. Users are able to control and set devices and values from this GUI, as well as access the control tools and GUIs associated with those devices.

The AO and telescope monitoring tool shown in Figure 6 was developed to improve AO operations efficiency during KI nights. Status indicators are used catch errors and changes in observing conditions. Links are provided to other frequently used tools.

An archive extractor and plotting tool has been developed to visualize arbitrary data recorded in the real-time data archive. This tool provides a graphical method for selecting times of interest and telemetry plotting in temporal and frequency space. The time to identity and investigate various aspects of system performance has been greatly reduced as a result of this tool. Figure 7 shows a screen shot of the GUI looking at an archive produced during the May, 2006 V^2 run. The horizontal dashed lines represent the status of the angle tracker and fringe tracker servo loops. The vertical lines represent a time span of interest; in this case the time span corresponds to a fringe sequence. Pressing the plot button produces a plot for each of the selected telemetry channels and plot types. Figure 8 shows the one-axis Keck I angle tracker error for the selected five minute time span in Figure 7.

Another data mining tool has been implemented through a log parsing tool which allows users to extract data from log files. Users are able to customize numerous aspects of the tool, such as developing and defining custom queries and devices, as well as specifying precise time periods, and methods of reporting. The data mining tool is capable of generating multiple types of charts as well as simple text reports which contain the summarized results of the executed query.

A generic tool has been developed to generate Python GUIs to perform a specific set of operations based on an input XML file. This allows the user to convert a well defined set of operations, within the XML file, into an interactive GUI. The XML definition can contain branching logic, widget definitions, external procedure calls, and a variety of other features.

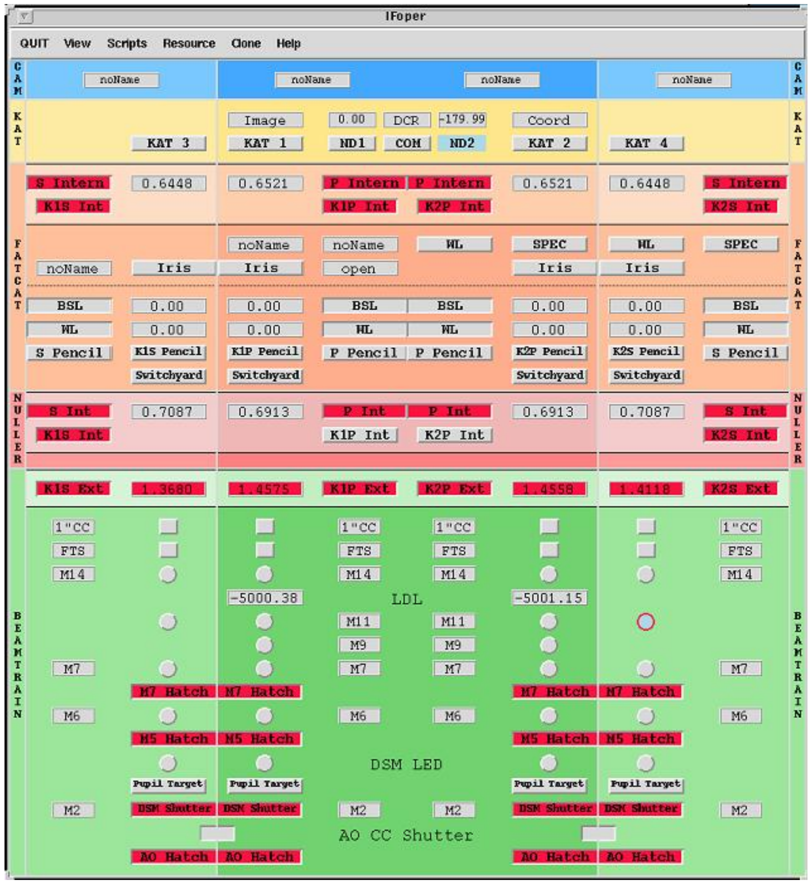

Figure 5 Interferometer operator motion control user interface.

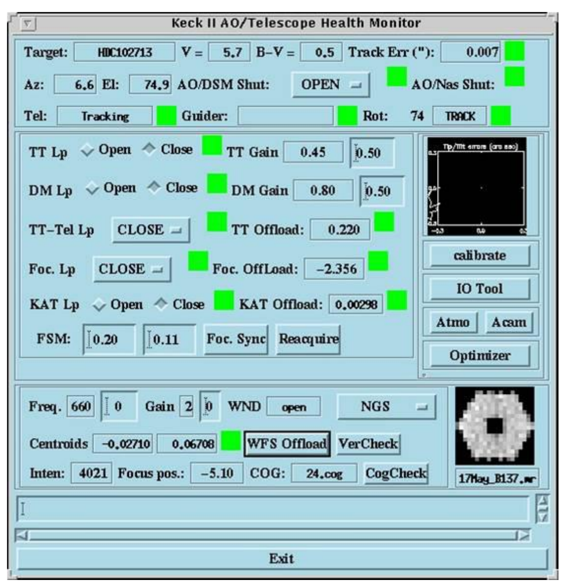

Figure 6 AO and telescope monitoring tool.

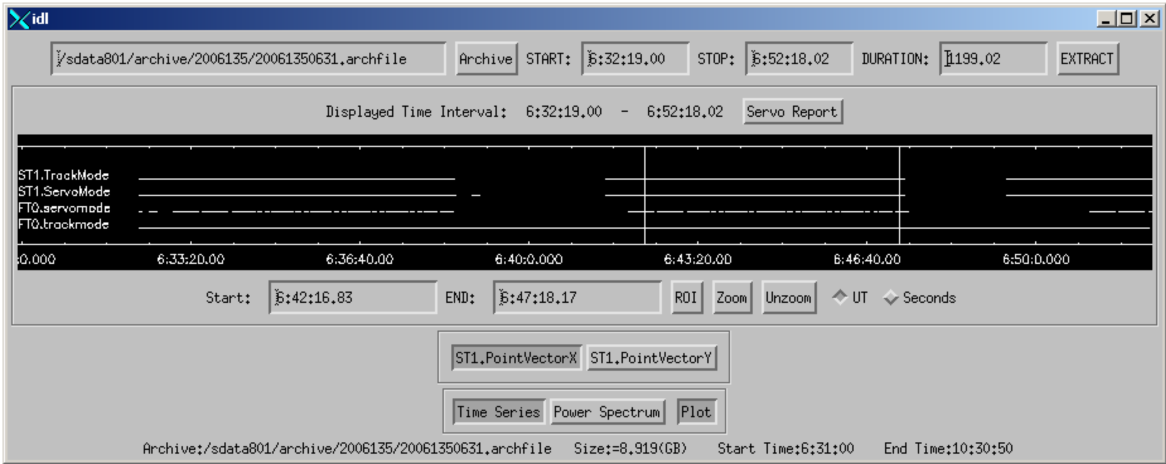

Figure 7 Extractor tool GUI for real-time data archive.

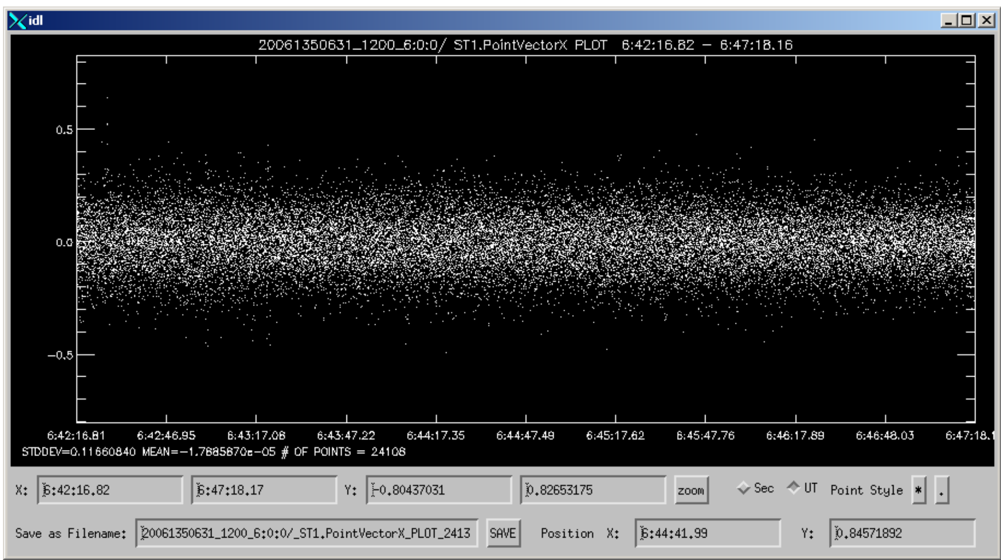

Figure 8 A plot of real-time data from the time sequence selected with the archive extractor tool.

The tool described in the previous paragraph was developed to support the currently ongoing effort to automate the alignment of the KI. A Python layer has been developed to produce a homogenous interface to the heterogeneous set of software controllable components involved in the alignment process. Beside the control of various components (shutters, targets, telescopes, etc.), the Python layer covers three main object classes:

- Sources: LEDs, white light stimuli, IF stimuli, AO stimuli, etc.
- Mirrors: Two degrees of freedom controlled by PMAC drives, picomotors, piezo actuators, etc.
- Cameras: Web-based video cameras, star tracker, cameras images, etc.

In order for the Python layer to access the various components, bridges to the Keyword (most EPICS components), CORBA (all real-time components) and HTTP-CGI (video camera servers) layers are used. This allowed the development of a generic alignment procedure that works on a triplet (source; mirror; camera); the source being iteratively aligned with the mirror on the camera. This generic alignment procedure, shown conceptually on the left of Figure 9, applied to a given triplet and wrapped with the appropriate beam train configuration is equivalent to an alignment step. All alignment steps are chained using the previously mentioned XML-based Python GUI generator. An example of an automated procedure for the alignment of the primary beam train is given on the right of Figure 9. The GUI guides the user through the list of automated steps. This auto-alignment tool has decreased the interferometer preparation time and the required personnel support for alignments.

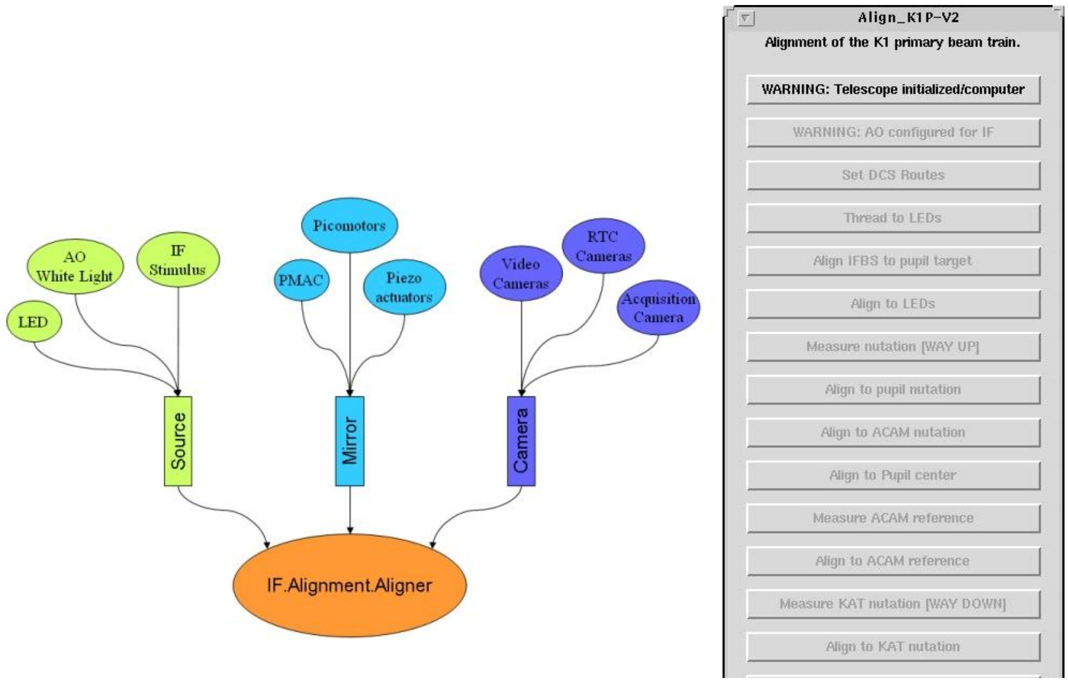

Figure 9 Left: Generic alignment procedure concept, where source, mirror and camera are standard interfaces for a heterogeneous set of objects. Right: Generated Python GUI for Keck I primary alignment in V^2 mode. All steps are fully automated.

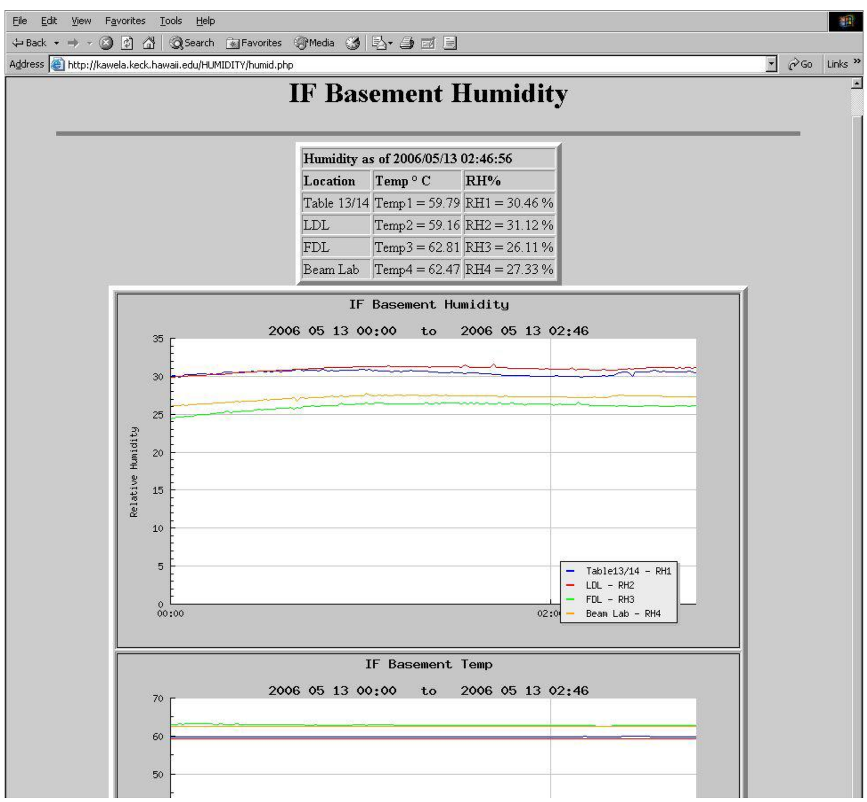

Figure 10 Humidity monitoring tool.

A logging tool has been developed to save and set mirror positions. The associated GUI allows users to save, set, and read the positions of mirrors from the primary and secondary beam train for both telescopes. The position history of the mirrors is also displayed, and a user is able to select a previous entry and reposition any number of the mirrors to their previous position. A user is also able to save the current position of any number of mirrors, allowing them to do testing and then return to their previous "good" position.

An EPICS application running on Solaris has been developed to monitor the KI basement humidity, the location of the long delay line carts and the state of the cryogen autofill system. A cronjob monitors application status and archives data from each of the devices. The data is automatically displayed for the user through web interfaces as shown in the example in Figure 10.

6. SYSTEM CHARACTERIZATION

A raster scan is routinely performed as part of each observing sequence in order to peak up the image from each telescope on the fiber that feeds light to the fringe tracker. This raster scan provides a real-time measurement of the combined performance of the AO system and interferometer beam train.[9] The raster scan is also routinely used to adjust beam-line focus. It has also proved to be a useful diagnostic for verifying beam train characteristics have been maintained after maintenance work has been performed. The user interface for this tool is shown in Figure 11. The left column shows the angle tracker images from each telescope, while the right column displays the fringe tracker raster images from the two telescopes. This tool is also used for automated target acquisition on the angle tracker camera.

Figure 11 Real-time image quality monitoring GUI.

A polarization test performed from the dual star module to the beam combiner confirmed that there were no significant polarization effects that would impact null depths to a level of 1 in 10,000.[9]

A system incorporating fifteen micro-g sensitivity accelerometers on each telescope was implemented some time ago for feed forward telescope piston compensation. These sensors are located throughout the telescopes, with six mounted on the primary mirror segments, three each on the secondary and tertiary mirrors, two on the AO bench and one on the dual star module as shown in Figure 12. This system also logs vibration information at 20 minute intervals, which is trended and analyzed. This data has led to changes in the control of the secondary mirrors, more frequent preventative maintenance of the hydrostatic bearing system, automated control of ventilation fans, and identification of fundamental vibration frequencies within the Observatory.

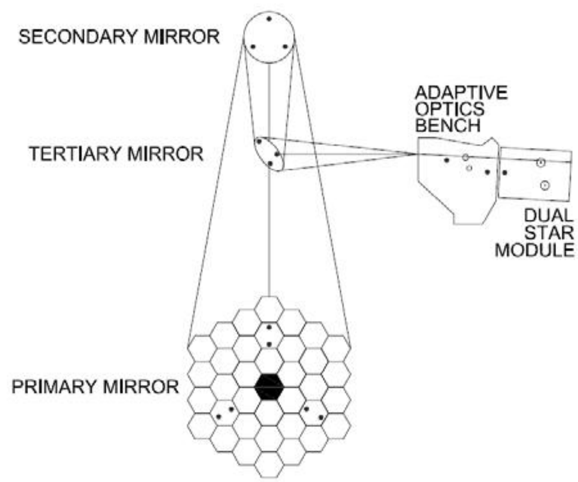

Figure 12 Accelerometer locations (each dot represents an accelerometer location).

7. SCIENCE SUPPORT

Science support for KI users is available from the MSC and includes proposal support, observation planning, data archiving, search and retrieval, and data reduction and calibration applications. The MSC KI support page can be found at http://msc.caltech.edu/software/KISupport/index.html. Science support updates include release of the public data archive and web interfaces to the planning and data reduction tools.

The public data archive currently includes data on approximately fifty-five science targets and their calibrators, ranging from main sequence stars and young stellar objects to active galactic nuclei.

The getCal planning tool (web interface at http://mscweb.ipac.caltech.edu/gcWeb/) includes functions for calibrator searches, determination of uv and baseline coverage, and spectral energy distribution fitting to automatically retrieved photometry. The package includes location and baseline information for six of the currently operating interferometers.

The V2calib data reduction package (web interface at http://mscweb.ipac.caltech.edu/webCalib/) takes the averaged, calibrated visibilities produced by the data pipeline and removes the system visibility. The output visibilities, available in FITS and ascii formats, are fully calibrated and ready for astrophysical interpretation. Both the getCal and V2calib packages are also available for installation on user's machines.

8. FUTURE PLANS

The emphasis over the next year will be on commissioning the nuller science mode with the operations readiness review scheduled for May, 2007.

Several performance improvements are in progress involving the Keck adaptive optics (AO) systems:

- The current dichroic beamsplitter that splits the light between the interferometer and the AO wavefront sensor loses about half the visible light. A new dichroic is being fabricated that should improve the visible light transmission to the AO system by ~ 50%.
- New wavefront controllers and sensors are under development for the AO systems.[7] These should improve both the sensitivity and bandwidth of the systems, as well as providing improved telemetry for optimization purposes. The new systems will have been implemented on both telescopes within the next year.
- The Keck II AO system is currently doing science with a laser guide star (LGS).[8] An improved version of this LGS system is under development for Keck I and should be on-sky by 2008.[7] LGS AO on both telescopes will provide improved performance on faint targets and remove the AO-imposed visible-wavelength magnitude limitation.

Several new science capabilities are under discussion:

- A second fringe tracker camera will be implemented in the interferometer lab as a spare for the existing camera. The availability of this camera would allow us to begin the process of implementing a phase referencing mode. In this mode the light from one object provides the fringe tracking information on the first camera while longer integrations can be taken of a science object with the second camera.
- An L-band (3-5 μm) camera has been developed for the differential phase science mode. This camera would be implemented in the basement to allow L-band visibility measurements.
- A proposal has been submitted to the NSF to implement phase referencing and astrometry with the two LGS AO equipped Keck telescopes. This proposal has several exciting science drivers including the measurement of general relativity effects around the black hole at the center of our galaxy via < 50 μarcsec astrometry.

ACKNOWLEDGEMENTS

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